

**THE DIRECTION OF CO(4→3) and CO(5→4) EMISSION FROM
132 0902+34, A POWERFUL RADIO GALAXY AT $z = 3.3995$**

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ABSTRACT

We report the detection of CO(4→3) and CO(5→4) emission from the powerful radio galaxy B2 0902+34 at a redshift $z_{\text{CO}} = 3.3995 \pm 0.0002$. The observed CO luminosity implies a mass of molecular gas, $M(\text{H}_2) \sim 4.5\text{--}5.6 \times 10^{10} h^{-2} \text{ M}_\odot$. These new observations, combined with the recent detection of strong far-infrared (rest-frame) continuum from the powerful radio galaxies 4C41.17 and B2 0902+34, suggest that at least some high- z powerful radio galaxies may be radio-loud analogs of hyperluminous infrared galaxies such as IRAS F10214+4724.

Subject headings: early universe - radio: galaxies - galaxies: interstellar matter -- galaxies: individual: B2 0902+34 -- radio lines: molecular

1. INTRODUCTION

Powerful radio galaxies at high redshift are potentially useful probes for understanding the properties of luminous galaxies in the early universe. Recent observations have shown that these systems possess strong rest-frame UV-to-optical emission lines, indicating that intense starbursts (e.g. McCarthy et al. 1987) maybe present in addition to the powerful AGN (e.g. Fales & Rawlings 1993). Large quantities of gas and dust may be required to power the star formation activity in addition to providing fuel for the powerful active nucleus (AGN). We report here the detection of CO emission from B20902+34 ($z \sim 3.4$), and an observation toward 4C 41.17 ($z \sim 3.8$). These objects were the first identified radio galaxies at $z > 3$ (Lilly 1988; Chambers, Miley, & van Breugel 1990) and remain two of the best studied high redshift galaxies. We compute the mass of H_2 gas from these CO data and compare the molecular gas mass and spectral energy distributions of these powerful radio galaxies with other luminous high redshift objects recently detected in CO.

2. OBSERVATIONS

Observations with the NRAO* 12m telescope were obtained during four separate observing periods between 1992, December and 1994, October. Observations at the IRAM 30m telescope were obtained during a single 2 day period in 1994, June. All of the observing sessions were

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marked by a high percentage of exceptionally good weather. System temperatures and observing frequencies, plus other relevant telescope and receiver parameters are listed in Table 1. The general system configuration and observing technique were similar at both telescopes. All observations were obtained using a nutating subreflector with a chop rate of ~ 1.25 Hz. Data were stored as either five or six minute scans, and a chopper wheel calibration was typically performed after every other scan. Pointing was monitored every few hours by observations of the planets and was estimated to be accurate to $4-3''$,

At the NRAO 12m telescope, data were obtained with the dual polarization 3mm receiver using two 512x2 MHz channel filterbanks, one for each polarization. There were problems with our initial observations that forced us to eventually discard half of the data from 1992, December, and to revise our method of taking data for subsequent observing runs. Instabilities in one of the two receiver polarizations occasionally produced low level noise spikes that, if not caught and eliminated from the data stack, could, after smoothing, mimic narrow ($\sim 50 - 100 \text{ km s}^{-1}$) lines. Even though the channel blocks that were thought to be affected were eventually eliminated, we chose to throw out all of the 1992, December data obtained with that polarization. We also decided to abandon our original attempt to double the velocity coverage of our observations by obtaining an equal amount of integration time for each source at three frequency settings, ν , and $\nu \pm \Delta\nu$ (where $\Delta\nu$ corresponded to a velocity shift of 500 km s^{-1}). The increased total velocity coverage ($\sim 2500 \text{ km s}^{-1}$) had been designed to allow for uncertainties (typically 0.1- 0.2%) in the reported redshifts for our sources. However, observations of a blank sky position at a fixed frequency revealed that, although the theoretical channel-to-channel rms was achieved in each filterbank for the longest integrations, we could not assume that the mean level was zero. Comparison of coadded data representing observations taken during consecutive 6-8 hr transits revealed that small, apparently random dc offsets and tilts in the baseline were often present at a level of a few $\times 0.1 \text{ mK}$. Had relatively strong ($> 1 \text{ mK}$) lines been present in any of our sources this method should still have served to increase our likelihood of achieving a detection. No such lines were detected. Instead, the large velocity shifts often had the effect of producing rather broad, pill box-shaped, phantom line profiles, and we therefore decided to drop our attempt to obtain extended velocity coverage on each source.

We chose to concentrate on observing those sources with redshifts determined from more than one line, or for which we had independent measurements from infrared spectra obtained at Mauna Kea. We obtained ~ 50 hours of data at the NRAO 12m telescope for two sources - B20902+34 and

4C 41,17- that are reported here. We also present observations of B2 0902+34 obtained with the I RAM 30m telescope during a short 2-day period in early summer 1994. At the I RAM 30m, both the 2mm and 3mm receivers were used to observe the CO(5→4) and CO(4→3) lines simultaneously. Given that the system temperature that was achieved with the old 3mm receiver (it was replaced shortly after our observations) was 2-3 times higher than that achieved in the 2mm band, only the 2mm data was sensitive enough to confirm the presence of the CO emission line in the 10-hours of integration that were obtained.

3. CO 1, UMINOSITY AND H₂ MASS

Figure 1 shows the CO(4→3) and CO(5→4) spectra of B2 0902+34 taken with the NRAO 12m and I RAM 30m telescopes respectively. Table 2 lists the measured line parameters. Given that the system temperatures for both observations were comparable, the increased aperture of the 30m yields slightly better S/N in one-fifth the integration time. The blue edge and the main peak are nearly identical for both line profiles. Indeed, the line shape and intensity of the main peak are consistent with recent measurements of the CO(4→3) line made at the Owens Valley Millimeterwave Interferometer (Yun & Scoville, private communication). However, the CO(5→4) line appears to show a red wing extending to $\sim 450 \text{ km s}^{-1}$ that is not as obvious in our CO(4→3) spectrum. Given the uncertainty in the full extent of the CO emission, Table 2 gives line parameters for both the main emission peak ($\sim 50 - 280 \text{ km s}^{-1}$) and the main peak plus the red wing ($\sim 80 - 450 \text{ km s}^{-1}$). From the measured values for both profiles we adopt a mean redshift, $\langle z_{\text{CO}} \rangle = 3.3995 \pm 0.0002$. This redshift corresponds to a luminosity distance of

$$D_L = c H_0^{-1} q_0^{-2} \left\{ z q_0 + (q_0 - 1) \left([2 q_0 z + 1]^{0.5} - 1 \right) \right\} = 13800 \text{ h}^{-1} \text{ Mpc}$$

and a lookback time 89% the age of the universe for $q_0 = 0.5$, where $H_0 = 100 \text{ h (km s}^{-1} \text{ Mpc}^{-1})$. For comparison, $D_L = 26100 \text{ h}^{-1} \text{ Mpc}$ and the lookback time is 77% the age of the universe for $q_0 = 0.02$.

The CO luminosity of a source at redshift z with an intensity of $S_{\text{CO}} \Delta \nu$ is,

$$L'_{\text{CO}} = \left(\frac{c^2}{2k\nu_{\text{obs}}^2} \right) S_{\text{CO}} \Delta \nu D_L^2 (1+z)^{-3},$$

where c is the speed of light and k is the Boltzmann constant. The measured ratio $L'_{\text{CO}}(5 \rightarrow 4)/L'_{\text{CO}}(4 \rightarrow 3)$ can be used to set constraints on the physical conditions in the molecular gas. Figure 2 shows the expected line ratios for an object at redshift 3.4 computed using a standard

LVG radiative transfer code and assuming a range of gas kinetic temperatures, $T_k = 30 - 200$ K, similar to what is observed in galactic molecular clouds. More appropriate here may be the range, $T_k = 40 - 80$ K, computed for the bulk of the gas and dust in extremely luminous infrared galaxies (e.g. Sanders, Scoville, & Soifer 1991; Solomon, Downes, & Radford 1992), and from recent studies of CO(4 \rightarrow 3) emission from the nuclei of nearby starburst galaxies (Güsten et al. 1993). Using $I'_{CO}(5 \rightarrow 4)/I'_{CO}(4 \rightarrow 3)$ from Table 2 gives a range of densities, $\log n(H_2) \sim 2.7 - 3.5 \text{ cm}^{-3}$, with $T_{ex} = 30 - 200$ K. With only two measured CO transitions, it is difficult to further constrain the gas excitation.

For molecular gas in gravitationally bound clouds, the ratio of the H_2 mass and the CO luminosity is given by $\alpha = M(H_2)/L'_{CO} \propto n(H_2)^{0.5}/T_b M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$, where $n(H_2)$ and T_b are the density and brightness temperature for the appropriate CO transition (e.g. Solomon, Radford, & Downes 1992). Multi-transition CO surveys of molecular clouds in the Milky Way (e.g. Sanders et al. 1993), and in nearby starburst galaxies (e.g. Güsten et al. 1993) have shown that hotter clouds tend to be denser such that the density and temperature dependence tend to cancel each other. The variation in the value of α is less than a factor of 2 for a wide range of gas kinetic temperature, gas densities, and CO abundance. If we adopt a value of $T_{ex} \sim 60$ K, and $\log n(H_2) \sim 3.2$, the value for α is $\sim 4 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$ similar to the value determined for the bulk of the molecular gas in the disk of the Milky Way (cf. Scoville & Sanders 1987). This implies a molecular gas mass for B20902+34 of,

$$M(H_2) = \alpha L'_{CO}(4 \rightarrow 3) = 4.5 - 5.6 \times 10^{10} h^{-2} M_\odot,$$

where the range in $M(H_2)$ represents the observed range for the measured CO(4 \rightarrow 3) intensity, 1.7 - 2.1 Jy km s $^{-1}$, reported in Table 2. This mass estimate is probably uncertain by at least a factor of 2.

With the observed brightness temperature, we can also make a rough estimate of the size of the CO emission region in B20902+34. The observed brightness temperature is diluted because the source does not fill the beam of the telescope. Taking $\Omega_{beam} = 60''$ at 104.8 GHz, an observed brightness temperature of $T_{mb} = 0.52$ mK, and assuming a brightness temperature for the gas of $T_b = 60$ K, the region of emission is

$$\Omega_{CO(4 \rightarrow 3)} = \left(\frac{T_{mb}(1+z)}{T_b[CO(4 \rightarrow 3)]} \right)^{0.5} \Omega_{beam} = 0.37''$$

in diameter which corresponds to $1.2 h^{-1} \text{ kpc}$ for $q_0 = 0.5$ ($2.3 h^{-1} \text{ kpc}$ for $q_0 = 0.02$). This calculation assumes that the gas is compact as opposed to being distributed in clumps.

The only other source to date that has been observed by us as extensively as B2 0902+34 is 4C 41.17. Figure 3 shows our 46 hour integration from the NRAO12m at the frequency corresponding to the redshifted CO(4→3) line (assuming the redshift as measured from [OIII] and Ly α). There is no evidence of an emission line above the 2σ noise level. However, it is still not possible to rule out the presence of broad, low-level emission with an integrated intensity nearly equal to that observed for B2 0902+34 (e.g. $T_R^*(\text{peak}) \sim 0.1$ mK and $A_V \sim 400$ km s $^{-1}$), or an emission line that falls outside the observed passband. The latter might be the case if, as in B2 0902+34, the CO emission line is redshifted by 500 km s $^{-1}$ from Ly α . Further observations of 4C 41.17 are needed before a more meaningful upper limit on the CO luminosity can be established.

4. DISCUSSION

The mass of molecular gas computed for B2 0902+34 is ~ 30 times larger than the mean molecular gas content determined for nearby, infrared bright spirals, including the Milky Way, and a factor of ~ 8 times larger than the largest molecular gas mass found for any isolated galaxies in the local ($z < 0.05$) universe (e.g. Solomon & Sage 1988; review by Young & Scoville 1991). However, the H_2 mass for B2 0902+34 is only $\sim 3-5$ times larger than the mean value determined for ultraluminous infrared galaxies at $z \lesssim 0.35$ (all of which appear to be mergers of gas-rich spirals) and comparable to the H_2 mass of the most gas-rich of these (e.g. the powerful radio galaxy 4C12.50 = PKS 1345-12; Mirabel, Sanders, & Kazès 1989); and the radio-loud QSO 3C 48; Scoville et al. 1993). Because B2 0902+34 is at an epoch when the universe was only $\sim 10\%$ of its current age, it is unclear if B2 0902+34 is similar to the most gas-rich mergers seen locally, or whether it represents an entirely different stage in galaxy evolution.

To better understand the properties of B2 0902+34, it is useful to summarize what has been found for powerful radio galaxies at lower redshift. Deep optical imaging of a complete sample of low z ($\lesssim 0.3$) powerful radio galaxies led Heckman et al. (1986) to conclude that a substantial fraction probably arise from the collision/merger of galaxy pairs, at least one member of which is a disk galaxy. Golombek, Miley, & Neugebauer (1988) found that a significant fraction of low z powerful radio galaxies are luminous far-infrared sources. From a study of a complete sample of 'warm' ultra luminous infrared galaxies, Sanders et al. (1988) suggested that luminous infrared galaxies, quasars, and powerful radio galaxies may represent an evolutionary sequence in the merger of gas-rich spiral galaxies. CO(1-0) emission and H I absorption (Mirabel 1989, Mirabel et al. 1989) confirmed the existence of dense concentrations of both atomic and molecular gas in the nuclei of

at least some powerful radio galaxies, while a more extensive survey of CO emission from powerful radio galaxies by Mozzarella et al. (1993) indicated that rich supplies of molecular gas may indeed be ubiquitous in powerful radio-selected galaxies detected by *IRAS*.

Whether the comparisons between powerful radio galaxies, luminous infrared galaxies, and QSOs at low redshift also hold at much higher redshifts is not clear, but it is instructive to compare the properties of B2 0902+34 with the only other luminous high redshift objects detected in CO - the hyperluminous infrared object *IRAS* F10214+4724 at $z \sim 2.3$ (Brown & vanden Bout (1991), and H1413+135 = the Cloverleaf quasar, at $z \sim 2.6$ (Barvainis et al. 1994). The computed H_2 mass for B2 0902+34 is only a factor of ~ 2.5 less than that determined from a multi-transition analysis of CO emission for *IRAS* F10214+4724 (Solomon, Downes, & Radford 1992), and a factor of $\sim 1 - 5$ less (depending on the amplification factor) than that computed for the gravitationally lensed Cloverleaf quasar. A comparison of morphological properties is less straightforward, but there is evidence that high- z powerful radio galaxies may be mergers (cf. Djorgovski et al. 1987; review by McCarthy 1993), and R band imaging of B2 0902+34 shows the galaxy to have a double peak profile (Eisenhardt & Dickinson 1993) that could be interpreted as a merger event. *IRAS* F10214+4724 appears also to be a strongly interacting system (Matthews et al. 1994).

Further evidence that powerful radio galaxies may be related to luminous infrared galaxies is provided by comparing the spectral energy distributions (SEDs) of high- z powerful radio galaxies with the hyperluminous infrared galaxy *IRAS* F10214+4724. Figure 4 summarizes the photometry (rest frame) for three of the best studied radio galaxies at $z > 3$ - B2 0902+34, 4C 41.17, and 6C 1232+39 - as well as data on *IRAS* F10214+4724. These data show that, (1) B2 0902+34 and 4C 41.17 may have a substantial far-infrared/submillimeter 'hump' as indicated by the apparent steep rise in luminosity from the radio core into the submillimeter, (2) the *IRAS* upper limits do not rule out the possibility that all three of these radio galaxies have bolometric luminosities comparable to *IRAS* F10214+4724, and (3) although the optical-to-UV spectra of the radio galaxies appear to be strongly affected by emission lines and reddening, the mean optical-to-UV luminosities of the radio galaxies are similar to *IRAS* F10214+4724. In the case of 6C 1232+39, the shape of the optical-to-UV spectrum is nearly identical to *IRAS* F10214+4724.

It is clearly premature to suggest that all high- z powerful radio galaxies are also powerful far-infrared emitters. It is also too early to suggest that all high- z powerful radio galaxies are rich in molecular gas, although our detection of CO emission from one of two objects suggests that a substantial fraction do. If the three radio galaxies shown in Figure 4 are representative of powerful

radio galaxies as a class, then these objects may represent a later stage in the evolution of some hyperluminous infrared galaxies. In such a scenario, the powerful radio jets occur when much of the dust and gas obscuring the central engine has been consumed by the AGN and/or turned into stars, clearing the way for hot plasma and radiation to escape.

4. CONCLUSIONS

Our detection of CO(4→3) and CO(5→4) emission from the powerful radio galaxy B20902+34 leads to the following conclusions:

(i) The CO luminosity of B2 0902+34 corresponds to $M(\text{H}_2) = 4.5\text{--}5.6 \times 10^{10} h^2 M_\odot$; the range reflects the uncertainty in the reality of the red line wing at velocities $\sim 280 \rightarrow 450 \text{ km s}^{-1}$. This H_2 mass is a factor of ~ 2.5 less than that computed for the hyperluminous IRAS galaxy F10214+4724, and is comparable to the H_2 mass computed for the most gas-rich ultraluminous infrared galaxies in the local Universe ($z \lesssim 0.3$).

(ii) The relative CO brightness temperature, $T_B(5 \rightarrow 4)/T_B(4 \rightarrow 3) \sim 0.50 - 0.64$, is consistent with optically thick CO emission with $T_{\text{ex}} \sim 60 \text{ K}$, and $\log n(\text{H}_2) = 3.2 \text{ cm}^{-3}$. The mean redshift of the CO emission from B20902+34, $z_{\text{co}} \simeq 3.3995$, is nearly identical to that of the CIV emission line, but is $\sim 500 \text{ km s}^{-1}$ redward of $\text{Ly}\alpha$. Our non-detection of CO emission from 4C41.17 may be due in part to centering the spectrometer passband at the observed redshift of $\text{Ly}\alpha$.

(iii) Currently available (IV-to-radio SEDs) for high- z radio galaxies suggest that these objects may have bolometric luminosities comparable to hyperluminous infrared galaxies. Recent reported detections of submillimeter emission from 4C 41.17 and B20902+34 may also imply that a substantial fraction of the bolometric luminosity of these radio galaxies is emitted at far-infrared (rest frame, $\sim 10 - 100 \mu\text{m}$) wavelengths. These observations, combined with our CO detection of B20902+34 suggest that at least some high- z powerful radio galaxies may be radio-loud analogs of hyperluminous infrared galaxies.

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Table 1. CO Observations

Parameter	4C 41.17	132 0902+-34	
	CO(4→3)	CO(4→3)	CO(5→4)
Telescope	NRAO 12m	NRAO 12m	IRAM 30m
Observing Dates (mm/yy)	12/92, 5/94, 10/94	10/93, 5/94	6/94
Center frequency (GHz) ^a	96.11024	104.85826	131.06530
Beamsize (FWHM'')	66	60	18
Spectral Bandwidth (MHz)	512	512	512
System temperature (K) ^b	180, 170, 200	220, 170	270
Total integration (hrs)	46	52	10

Note: Source positions: 4C 41.17- $\alpha(1950)$, $6^h 47^m 20.79^s$; $\delta(1950)$, $41^\circ 34' 04.5''$
 B2 0902-34 - $\alpha(1950)$, $9^h 02^m 24.77^s$; $\delta(1950)$, $34^\circ 19' 57.8''$

^aCorresponding to velocity 0 km s⁻¹ at heliocentric redshift $z = 3.797$ (4C 41.17), and $z = 3.3968$ (B2 0902-34).

^bMean system temperature during the observing run (mm/yy) - T_R^* scale (NRAO); T_A^* scale (IRAM).

Table 2. CO Line Parameters - B2 0902+34

Quantity (1)	CO(4→3)		CO(5→4)	
	(2)	(3)	(4)	(5)
$T_{mb}(\text{peak})(\text{mK})$	0.52 ± 0.14		2.15 ± 0.38	
$\Delta v_{co}(\text{FWHM})(\text{km s}^{-1})$	140 ± 30	...	140 ± 30	...
$\Delta v_{co}(\text{FWZI})(\text{km s}^{-1})$	200 ± 50	330 ± 50	200 ± 50	350 ± 50
$I_{co}(\text{K km s}^{-1})$	0.067 ± 0.017	$0.08530.02$	0.27 ± 0.04	$0.4540.08$
$S_{co}\Delta v(\text{Jy km s}^{-1})$	1.7 ± 0.45	2.1 ± 0.57	1.3 ± 0.22	2.1 ± 0.36
$\langle z_{co} \rangle$	3.3992	3.3993	3.3992	3.3998
$D_l, (\text{h}^{-1} \text{Gpc})$	13.8^\dagger		13.8^\dagger	
$L'_{co} (10^{10} \text{ h}^{-2} \text{K km s}^{-1} \text{pc}^2)$	1.130.3	1.440.4	0.55 ± 0.10	0.90 ± 0.16
$I_{co} (10^7 \text{ h}^{-2} \text{Jy})$	3.640.9	4.44,1.2	3.2 ± 0.58	5.4 ± 1.0
$L'_{co} (5 \rightarrow 4) / L'_{co} (4 \rightarrow 3)$	0.50 ± 0.16	0.64 ± 0.21

† Luminosity distance computed using $H_0 = 100 \text{ h} (\text{km s}^{-1} \text{Mpc}^{-1})$, $q_0 = -0.5$, and $z_{co} = 3.3995$. Luminosity values for $q_0 = 0.02$ can be computed by multiplying the above numbers by 3.6.

Column (1) - Quantity measured from data in Figure 1.

Columns (2)&(4) - main peak ($\sim 80\text{--}280 \text{ km s}^{-1}$)

Columns (3)&(5) - main peak plus red wing ($\sim 80\text{--}450 \text{ km s}^{-1}$)

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Figure Captions

Figure 1. (top) CO(4 \rightarrow 3) spectrum from the NRAO12m telescope. (bottom) CO(5 \rightarrow 4) spectrum from the IRAM 30m telescope. The spectra have been smoothed to a resolution of 69 km S-l. Redshifts for Ly α ($z = 3.393$; Lilly 1988), III absorption ($z = 3.3968$; Uson et al. 1991; Briggs et al. 1993) and CIV emission (3.399; Lilly 1988) are indicated along with the red shift of velocity-weighted mean CO emission for each line.

Figure 2. The CO(5 \rightarrow 4)/CO(4 \rightarrow 3) brightness temperature ratio as a function of 11_2 density for gas kinetic temperatures of 30, 60, 100, and 200 K as determined using a 15-level LVG calculation with $X(\text{CO})/(dv/dr) = 3 \times 10^{-5} \text{ (km s}^{-1}\text{pc}^{-1})^{-1}$ and a microwave background temperature of 11.8 K.

Figure 3. CO spectrum toward 4C 41.17 smoothed to a resolution of 80 km s-l. Redshifts for Ly α ($z = 3.800$; Chambers et al. 1990) and O[III] emission (3.797; Fales & Rawlings 1993) are indicated.

Figure 4. Rest-frame SEDs for high- z powerful radio galaxies and the hyperluminous infrared galaxy F1 0214+4724. The data for F1 0214+4724 are from Rowan-Robinson et al. (1993), except for the more recent 20 μ m measurement from Telesco (1994). For the radio galaxies the data are as follows: IRAS upper limits were determined by us from ADDSCAN/SCANPI processing (Helou et al. 1988) of the far-infrared data; the submillimeter data are from Chini & Krügel (1994), Dunlop et al. (1994), and Fales, Rawlings, & Dickinson (1993); the radio data are from the NED database at IJAC, except for 4C41.17 (Dunlop et al. 1994); the near-ir/optical data are from Lilly (1988) and Eisenhardt & Dickinson (1992) for B2 0902-34, from Chambers et al. (1990) for 4C 41.17, and from Fales et al. (1993) for 6C1232+39 ($z = 3.2$). Arrows indicate reported upper limits. Downward straight lines indicate continuum level after subtraction of estimated contribution from optical emission line(s) (e.g. Eisenhardt & Dickinson 1992; Fales & Rawlings 1993; Graham et al. 1994). Open symbols represent emission from the extended radio lobes (as distinct from the radio core) as given in Dunlop et al. (1994) for 4C 41.17, and as measured by us from the maps of B2 0902434 presented in van Breugel and McCarthy (1990). Similar data were not available for 6C 1232+39.

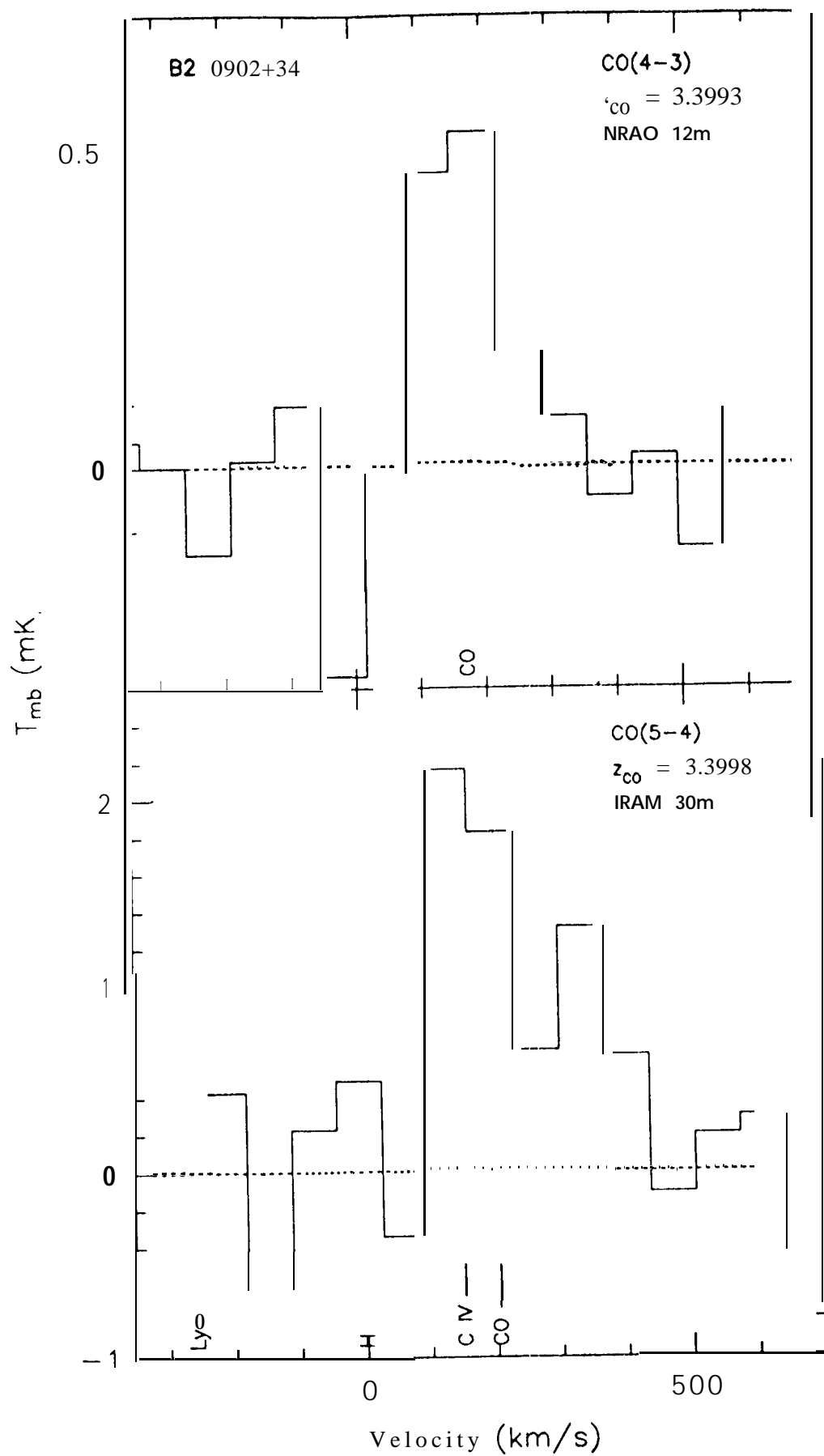


Figure 1.

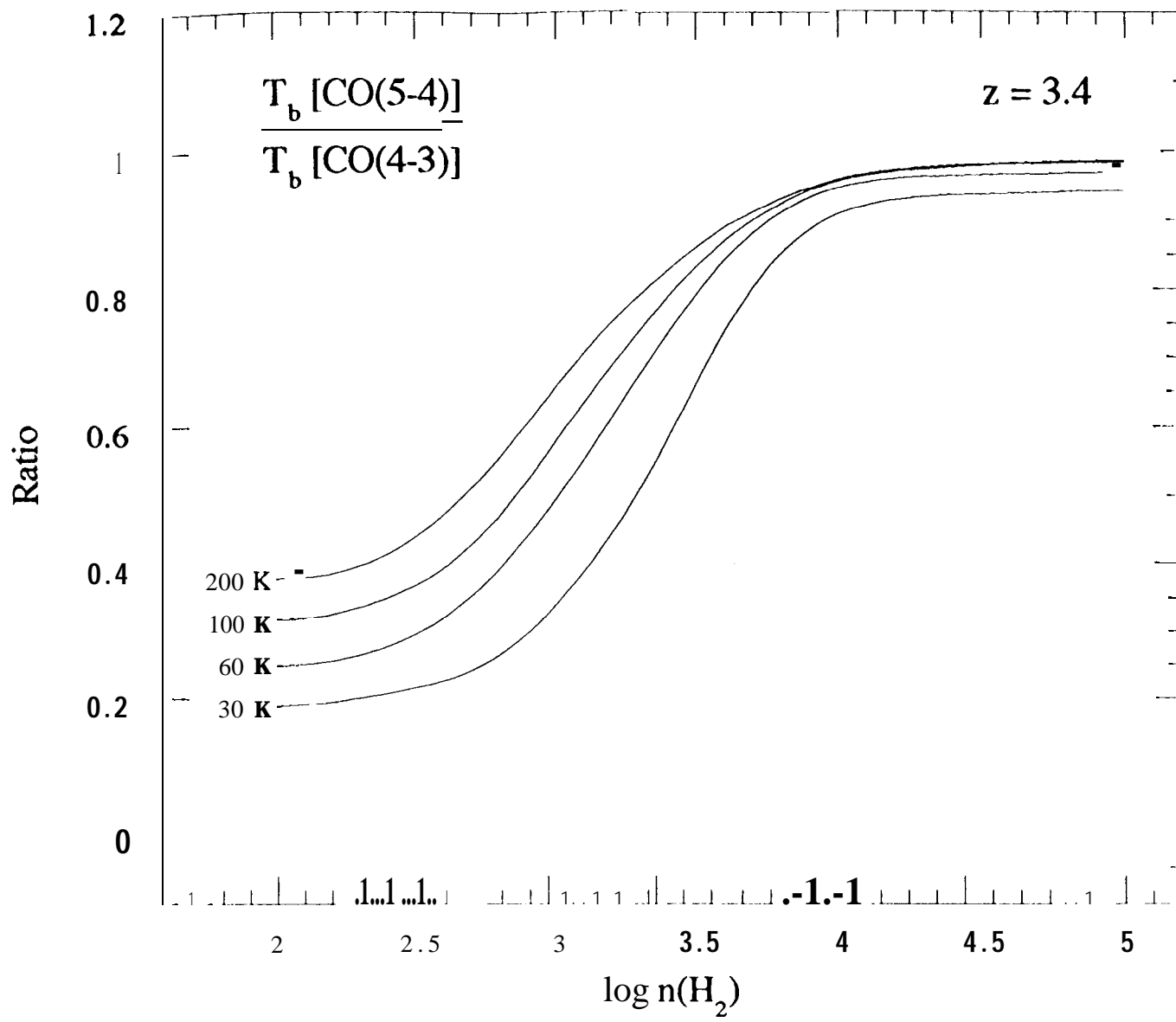


Figure 2.

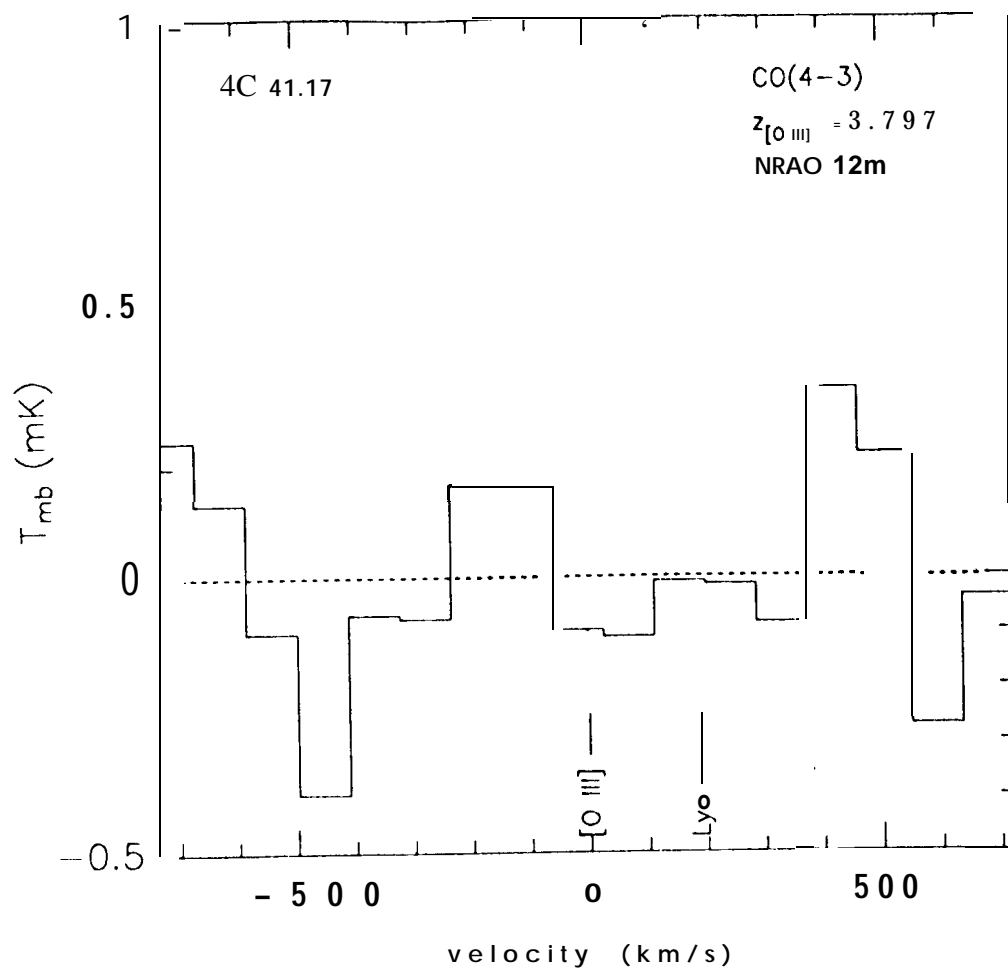


Figure 3.

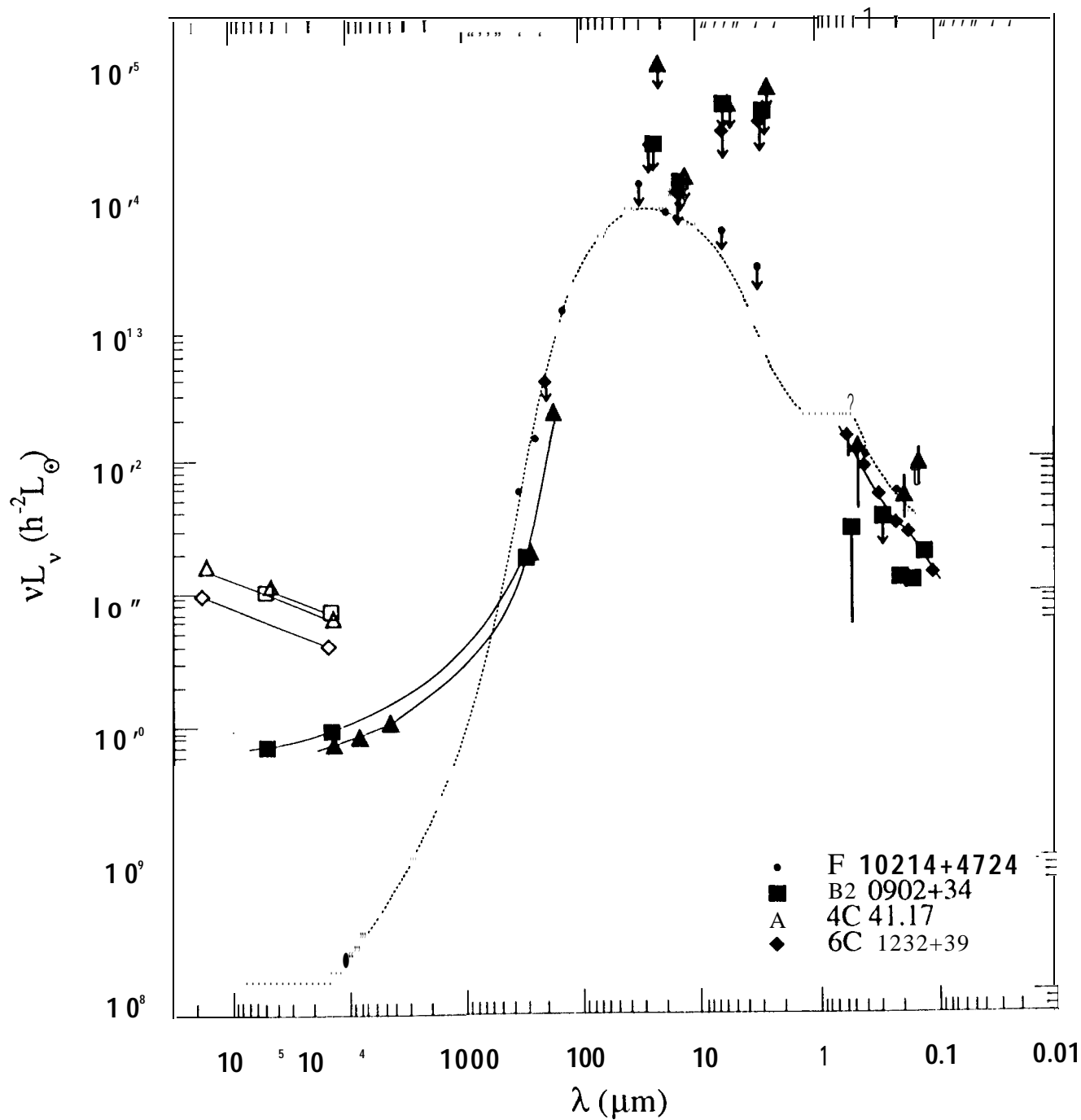


Figure 4.